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The effect of wire electrical discharge machining on the fatigue life of Ti-6Al-2Sn-4Zr-6Mo aerospace alloy

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Abstract

The paper details experimental data for the fatigue behaviour of aeroengine alloy Ti-6Al-2Sn-4Zr-6Mo following wire electrical discharge machining (WEDM), with minimum damage generator technology and optimised trim pass strategies. Comparative results for flank milled samples are also given together with associated micrographs detailing workpiece subsurface integrity and fracture initiation. Despite a marginally higher S-N response for the milled specimens compared to the wire machined samples when subject to a finishing regime, linear regression statistical analysis suggested no significant difference in performance at the 5% level based on slope responses. Micrographs showing sample crack initiation sites and fatigue crack growth paths suggest a 40-50µm altered zone in fracture surfaces for milled specimens with fatigue striations defining the crack path. For WEDM surfaces, crack initiation was in some cases due to defects below the machined surface, with secondary cracks probably due to local stresses.

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Keywords: Titanium alloys; wire electrical discharge machining; fatigue; surface integrity

1. Introduction

The understandable 'risk averse' stance of the aerospace industry is such that the lead-times for adoption of newer or speculative manufacturing technologies over currently validated production processes are inherently longer than say in the automotive sector and require more exhaustive research, analysis and development. However with current / future growth forecasts in the aerospace sector approaching 4% annually [1], it is questionable whether process optimisation through continuous improvements in existing operations, which generally provide only incremental rather than step changes, will be adequate to meet increased productivity demands. One example is the machining of aeroengine blade root slot configurations in turbine / compressor discs (see Figure 1(a)), which is currently carried out largely using broaching. While capable of providing the necessary component quality and functional requirements, the process has significant drawbacks not least in terms of machine tool / tooling costs, setup / changeover times and cutting forces / power requirements etc. Research and development on alternative processing methods over the last 10 years has encompassed both conventional and non-conventional machining technologies involving form milling configurations using both solid and indexable tooling, abrasive techniques including cup grinding, point or pencil grinding or electrolytic point grinding, waterjet cutting and more recently wire electrical discharge machining (WEDM), whether solely or in combination [2-4]. Alternative universal solutions are complicated by the fact that disc materials encompass nickel based superalloys and advanced titanium alloys and whereas form milling may be

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acceptable for the latter, its production use for superalloys may be constrained by considerations of productivity and tool life in respect of achieving the necessary slot form accuracy and integrity. With processes such as EDM, restrictions here primarily centre on received wisdom relating to adverse workpiece surface integrity effects and compromised fatigue response. Existing use of EDM technology for aeroengine manufacture is currently limited mainly to die-sink operations for the production of cooling holes in turbine blades as well as seal grooves on nozzle guide vane components, which are typically located in low stress regions or subject to a secondary finishing regime. While the thermal nature of the EDM process can indeed cause a degree of workpiece damage, the extent is often exaggerated and largely influenced by historical perceptions.

Developments over the last decade in EDM generator technology however, involving ultra high frequency pulse discharges and process operating strategies have made possible the generation of near damage/defect free workpiece surfaces [5]. Additional advantages relate to lower capital equipment / consumables cost, the possibility of 24 hour operation and flexibility in relation to slot format (software driven) etc. Figure 1(b) shows laboratory based WEDM machining of disc fir-tree root profiles. The following experimental work assessed four-point bend fatigue performance for WEDM and conventionally machined flank milled titanium specimens.

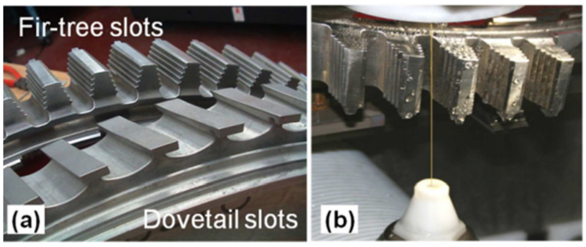

Fig. 1. (a) Sample blade root slots in turbine discs, (b) WEDM of fir-tree root slot

2. Experimental work

2.1. Workpiece materials and general equipment

Workpiece material was a titanium alloy Ti-6Al-2Sn-4Zr-6Mo (Ti6246), see Table 1 for nominal composition [6]. Developed in the 1960's, this high strength, high toughness heat treatable α+β alloy is used for gas turbine components operating at moderate temperatures (typically < 400°C), in the low pressure (LP) and high pressure (HP) compressor such as forged discs [7, 8].

Table 1. Nominal chemical composition of Ti-6Al-2Sn-4Zr-6Mo [6]

Element	Al	Sn	Zr	Mo	N	C	H	Fe	O	Ti
Percentage	6	2	4	6	0.04	0.04	0.0125	0.15	0.15	bal

The material was supplied in the form of an engine compressor disc which had been subjected to solution treatment for 2 hours at 910°C followed by aging for 8 hours at 595°C to provide a bulk hardness of ~HV380. See Fig. 2 for workpiece material microstructure and sample disc section prior to fabrication of fatigue specimens.

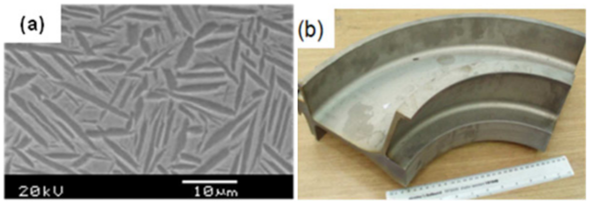

Fig. 2. Microstructure of Ti6246 workpiece material

Wire machining was carried out using an Agie-Charmilles Robofil 240cc 5-axis unit employing 'Clean Cut' generator technology, while a Matsuura FX5, 3-axis vertical high speed CNC machining centre was utilised for flank milling benchmarking specimens. During wire machining the de-ionised water dielectric conductivity was maintained at ~5µS/cm. The wire used was 250µm diameter uncoated brass. Workpiece surface roughness was measured using a Taylor Hobson Form Talysurf 120L with a 0.8mm cut-off and 4mm evaluation length. Topographic 3D workpiece profiles were mapped over 1mm^2 using 6.13µm line spacing. Fractography analysis was conducted on a JEOL 6060 scanning electron microscope (SEM). Surface residual stress measurements were performed using a Proto iXRD machine based at the University of Manchester.

2.2. Specimen production and fatigue test conditions

Fatigue specimen size was 8 x 8 x 56mm due to material supply size limitations as average disc web thickness was ~ 9mm, with WEDM test surfaces machined using roughing plus 2 finishing (trim cut) passes. The EDM operating parameters employed were based on those previously reported by Antar et al. [5] involving a 4 trim pass strategy, which incorporated the generator's titanium technology database with modifications to ensure the surface roughness (Ra) after the second finishing pass (T2) was < 0.8µm. Typically surface roughness following the roughing pass was in the region of ~3.2µm Ra while for T1 and T2 trim passes, the values were ~ 2.0µm and 0.6µm Ra respectively. Additionally, average recast layer thickness following T2 was typically ≤ 2.0µm.

Flank milled samples were machined using 5 passes with 0.1mm depth of cut at each step. The 10mm diameter end mill utilised was a multi-layered PVD coated carbide tool, and the wet machining operation employed typical aerospace cutting parameters / conditions. All other surfaces on both the wire machined and flank milled specimens were ground (Jones and Shipman 540AP surface grinder using a SiC wheel) to ~0.3µm Ra with dimensional accuracy of ±20µm between the test surface and its opposite side. The longitudinal corners between the test surface and the ground surfaces were machined using a 1mm radius milling tool. A total of 40 specimens were produced for the research. In related published work involving the fatigue life of Udimet 720 nickel based superalloy following wire electrical discharge machining [9], both roughing and finishing regimes were evaluated in addition to milling. Understandably however, the roughing operation provided a fatigue performance significantly inferior to that of the milled surfaces and therefore in the present work only specimens subject to finishing/trim passes were evaluated.

Fatigue tests were conducted using a four-point bend arrangement which maintained maximum stresses on the test surface; see Figure 3 for experimental setup. All tests were performed at room temperature (20^{o}C) on an Amsler Vibrophore electro-magnetic resonance testing machine. The test frequency varied between 69-79Hz (HCF) depending on the applied stress level, with specimen run-out being defined as 1.2 x 10^7 cycles.

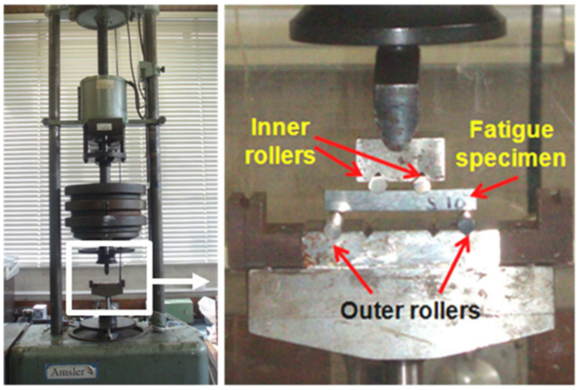

Fig. 3. Experimental setup of 4-point bend fatigue test

Maximum applied stress varied between 55% and 95% of the workpiece material's ultimate strength, with a stress ratio R of 0.1. The trials were carried out at 6 stress levels with 3 repetitions at each. Testing necessitated adjustment of the cell load and tuning of the machine's servo gain in order to achieve maximum stress levels. In addition, the smaller than normal fatigue specimens (8 x 8 x 56mm as opposed to 10 x 10 x 70mm) necessitated manufacture of appropriate jigs and rollers.

3. Results and discussion

Figure 4 details the S-N curves for the WEDM and milled fatigue specimens. The data suggest relatively similar fatigue life for both processes at the highest stress levels with evident variation between the two at intermediate / low applied stresses. The fatigue run-out (1.2x10^7) for the WEDM specimens were recorded at an endurance limit to ultimate tensile strength ratio of 0.59 while for milling the ratio was 0.62. This was in good agreement with other α-β titanium alloys such as Ti-6Al-4V where the ratio is reported to be ~0.63 [10]. The S-N curves of the two processes also suggest low variation in the number of cycles to failure at the same stress levels, which also points toward consistency of the machining operations.

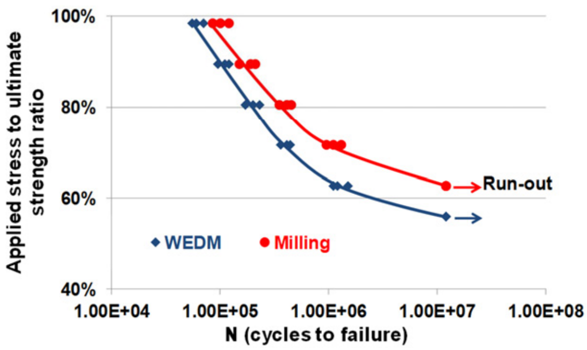

Fig. 4. S-N fatigue curves for Ti6246 specimens

Linear regression statistical analysis together with t-test calculations were employed to assess whether variations in the fatigue life results between the two processes were significant. This entailed calculating the variance for each curve (using $\log_{10}$ values), from which the pooled variance for each curve to be compared was found. Subsequently, the t_{calc} values for the gradient and the intercept for each comparison combination were estimated and compared with tabulated values (t_{tab}) such that $t_{calc} < t_{tab}$ indicated a statistically non-significant result. A $\log_{10}$ plot of the fatigue curves is detailed in Figure 5. Subsequent statistical analysis suggested no significant differences in the slope (t_{tab} = 2.021 and t_{calc} = 1.541) of both the fatigue curves at the 5% level. This was similar to results for Udimet 720 nickel based superalloy [9]. In contrast, intercept values proved significant (t_{calc} = 4.251), however the analysis was based on a y-intercept at $\log_{10}$ N = 0, which has no practical relevance (i.e. 1 cycle to failure). Therefore, a subsequent regression calculation was considered for the y-intercept at $\log_{10}N = 5$ (i.e. 10^5 cycles to failure). Here, the results highlighted no significant differences for the intercept parameters with $t_{calc} = 1.005$.

At the low applied stress levels, the fatigue run-out strength of the milled specimens was ~ 12% higher than the WEDM-ed surfaces. This was most likely the result of a more favourable residual stress state in the former. In ancillary tests undertaken to determine the effect of discharge pulse shape on WEDM performance (not shown here), measurement of surface residual stress following T1 and T2 passes produced moderate tensile (< 100MPa) and nominal neutral to low compressive stress levels (not more than -100MPa) respectively. This somewhat surprising result for T2 bearing in mind the non-contact / thermal nature of the process, could have been due to some overriding initial stress state from the forging operation. There were however also differences in the surface roughness produced as a result of the WEDM and milling processes (Ra 0.26μm for milling and 0.60μm for WEDM, both in transverse direction), although previous work undertaken by Novovic [11] suggests that with average surface roughness ≤1.24μm, the surface residual stress regime would be expected to override roughness considerations.

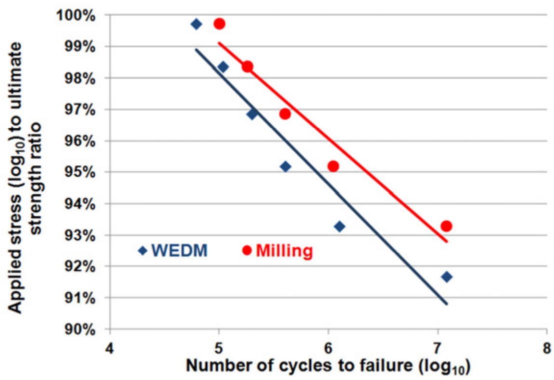

Fig. 5. Log_{10}-$\log_{10}$ fatigue curve plots for Ti6246 specimens

According to Evans et al. [12] and Zhuang and Halford [13], the compressive residual stresses at the machined surfaces subject to HCF loading can be reduced by over 50% following a few cycles due to the plastic deformation of the material which reduces the misfits between the compressed layer and the underlying bulk layer. The amount of stress relaxation is dependent on the magnitude and distribution of initial stresses, the degree of cold working, the applied mean stress / stress range, and the material's cyclic stress-strain behaviour.

Figures 6 and 7 show a sample crack initiation site and fatigue crack path for a WEDM and milled fracture surface respectively. For the WEDM specimens, the majority of fatigue failures occurred at the machined surface with the depth of crack initiation sites typically measuring ~50μm. Analysis of sparked surfaces highlighted no apparent cracking however the absence of significant compressive stresses would be expected to cause failure at or near the workpiece surface. Similarly, a ~40-50μm altered zone can be observed at the fracture surface of the milled specimens, while fatigue striations are also obvious and define the fatigue crack path.

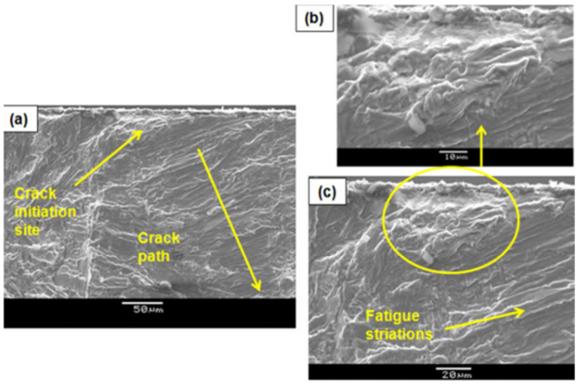

Fig. 6 (a-c). SEM micrographs showing Ti6246 fracture surface / crack initiation site in a WEDM specimen

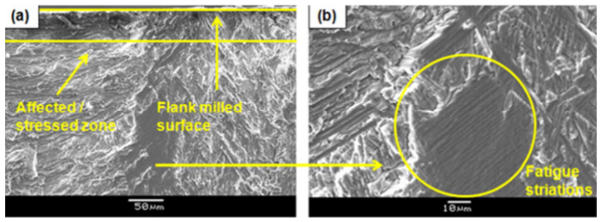

Fig. 7 (a-b). SEM micrographs showing Ti6246 fracture surface / crack initiation site in a flank milled specimen

Conversely, Figure 8 details a WEDM fracture surface with a crack initiation site due to an anomaly / defect below the machined surface. Secondary cracks, probably due to local stresses, can also be observed in Figure 9. It was not possible to obtain cross-sectional micrographs for specimens that did not fail during the test, as any wire cutting (sectioning) would have damaged the surface and not revealed any possible crack initiation / fatigue features.

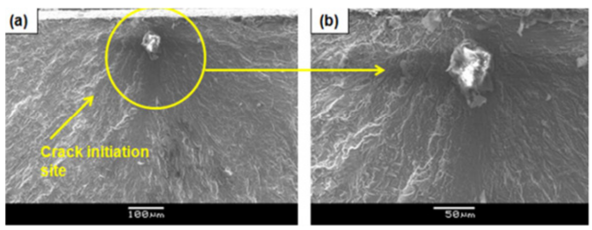

Fig. 8 (a-b). SEM micrographs showing crack initiation due to an 'abnormality' in Ti6246 WEDM specimen

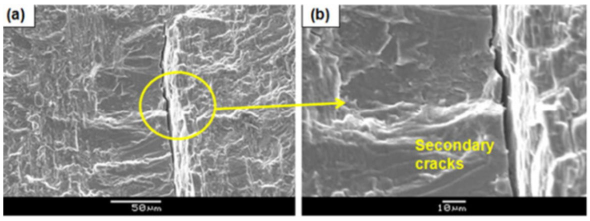

Fig. 9 (a-b). SEM micrographs showing secondary cracks at Ti6246 fracture surface

4. Conclusions

- When using minimum damage EDM generator technology and optimised trim-pass strategies, no statistically significant variation in fatigue performance was evident between WEDM finishing (a roughing and two finishing pass sequence) and flank milling of Ti6246 specimens based on $\log_{10}$-$\log_{10}$ slope data.
- The slight variation in fatigue life between the two S-N curves which was more evident at low applied stress levels was in all likelihood due to differences in residual stress state. Variations in surface roughness between the two (Ra 0.26µm for milling and 0.60µm for WEDM, both in transverse direction) was unlikely to have been a factor.
- Fractography data revealed that for specimens machined using both processes, crack initiation was predominantly within the first 40-50µm from the surface despite the absence of any major machining related damage (cracks, laps etc.). This would also suggest only moderate levels of compressive surface residual stress in the case of milled specimens.

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References

[1] Kappmeyer, G., Hubig, C., Hardy, M., Witty, M., Busch, M., 2012. Modern machining of advanced aerospace alloys - Enabler for quality and performance. Procedia CIRP 1, p. 28-43.

[2] Curtis, D.T., Soo, S.L., Aspinwall, D.K., Huber, C., Fuhlendorf, J., Grimm, A., 2008. "Production of complex blade mounting slots in turbine disks using novel machining techniques," Proceedings of the 3rd International Conference on High Performance Cutting-CIRP HPC. Dublin, Ireland, p. 219 – 228.

[3] Aspinwall, D.K., Soo, S.L., Berrisford, A.E., Walder, G., 2008. Workpiece surface roughness and integrity after WEDM of Ti-6Al-4V and Inconel 718 using minimum damage generator technology, Annals of CIRP 57/1, p. 187.

[4] Curtis, D.T., Soo, S.L., Aspinwall, D.K., Sage, C., 2009. Electrochemical superabrasive machining of a nickel-based aeroengine alloy using mounted grinding points, Annals of CIRP 58/1, p. 173.

[5] Antar, M.T., Soo, S.L., Aspinwall, D.K., Cuttell, M., Perez, R., Winn, A.J., 2010. "WEDM of aerospace alloys using 'Clean Cut' generator technology," Proceedings of the 16th International Symposium on Electromachining (ISEM XVI). Shanghai, China, p. 285-290.

[6] Donachie Jnr., M.J., 2000. Titanium: A Technical Guide, 2nd Edition, ASM International, Ohio.

[7] Eβlinger, J., Helm, D., 2003. "Titanium in aero-engines," Proceedings of the 10th World Conference on Titanium: Ti-2003: Science and Technology, 2003, Hamburg, Germany: Wiley-VCH, p. 2847-2852.

[8] Boyer, R., Welsch, G., Collings, E.W., 1994. Materials Properties Handbook: Titanium Alloys, ASM International, Ohio.

[9] Antar, M.T., Soo, S.L., Aspinwall, D.K., Sage, C., Cuttell, M., Perez, R., Winn, A.J., 2012. Fatigue response of Udimet 720 following minimum damage wire electrical discharge machining, Materials and Design 42, p. 295.

[10] Tokaji, K., Bian, J.-C., Ogawa, T., Nakajima, M., 1996. The microstructure dependence of fatigue behaviour in Ti15Mo5Zr3Al alloy, Materials Science and Engineering: A 213(1-2), p. 86.

[11] Novovic, D., 2004. The effects of machined workpiece surface topography and integrity on fatigue life: PhD thesis, University of Birmingham, Birmingham, UK.

[12] Evans, A., Kim, S.B., Shackleton, J., Bruno, G., Preuss, M., Withers, P.J., 2005. Relaxation of residual stress in shot peened Udimet 720Li under high temperature isothermal fatigue, International Journal of Fatigue 27(10-12), p. 1530.

[13] Zhuang, W.Z., Halford, G.R., 2001. Investigation of residual stress relaxation under cyclic load, International Journal of Fatigue 23(Supplement 1), p. 31.